

LARGE IRREGULARITIES OF RAWINSONDE ASCENSIONAL RATES WITHIN 100 NAUTICAL MILES AND THREE HOURS OF REPORTED CLEAR AIR TURBULENCE

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ABSTRACT

The assumption that a rawinsonde balloon system may experience large changes in its rate of ascent, as compared to the average rate for the observation, while traversing a region of clear air turbulence is investigated. In a 5-day period a well-defined region of turbulence, concentrated near a trough, progressed eastward for several successive synoptic observations. Rawinsonde ascensional rates are studied for 20 stations located within and outside this turbulent region for layers 2,000 ft. to 2,500 ft. thick between about 20,000 ft. and 45,000 ft. in altitude. Those rawinsonde observations within the turbulent region show much larger ascensional rate changes between layers, compared to the average for the observation, than do those outside the turbulent region. Furthermore the observations showing these large variations progress eastward with time corresponding generally to the eastward motion of the turbulent region.

A large change or variation is defined as one for which the change in ascensional rates between adjacent layers is 25 percent or greater of the average ascensional rate for the observation. This value is about 2.5 times the standard deviation for the total population of these changes, about 2,100 observations, and about four times the estimated standard deviation of the errors involved in the pertinent rawinsonde observations.

This study is being extended to cover a larger portion of the United States for special clear air turbulence collection periods. If a relationship between clear air turbulence and large ascensional rate variations is established, it may be possible to use these data on a real time basis to detect and track clear air turbulence.

1. INTRODUCTION

For several years the United States Weather Bureau [1] has screened aviation pilot reports from all reporting aircraft for cases of clear air turbulence. These cases have been tabulated chronologically giving date, time, latitude, longitude, altitude, and intensity. In addition these reports have been plotted on the maximum wind analysis charts for a 12-hr. period centered on the hour of the chart. These plotted maps and other studies [2], [3] suggest that moderate to severe clear air turbulence sometimes occupies rather large regions of the atmosphere and may last for several hours. If this is true it is reasonable to assume that a rawinsonde balloon may pass near or through a turbulent region, and in so doing may experience large changes in rate of ascent through this region as compared to the average rate for the observation. An investigation of this assumption is underway to discover if large irregularities in balloon ascensional rates occur during those rawinsonde observations which corre-

spond in time and location to regions of reported clear air turbulence.

A 5-day study situation (beginning November 7, 1963) was selected from the clear air turbulence maps. This situation involved a well-developed trough with a jet stream moving around it. As the trough moved eastward, a region of moderate to severe turbulence in the region of the trough could be interpreted as moving eastward across several rawinsonde stations over a period of several successive observations. A few scattered occurrences of turbulence occurred both upstream and downstream. This study has been confined primarily to the region of the trough as it progressed eastward. Rawinsonde balloons which were released near the time the trough passed the station almost certainly traversed the turbulent region. It seems reasonable to assume that their rates of ascent would be influenced by large-scale motions, if such existed, within this turbulent region. A rawinsonde balloon would be less likely to traverse the more scattered regions downstream from the trough though on occasion turbulence was reported near the place and time of such an observation.

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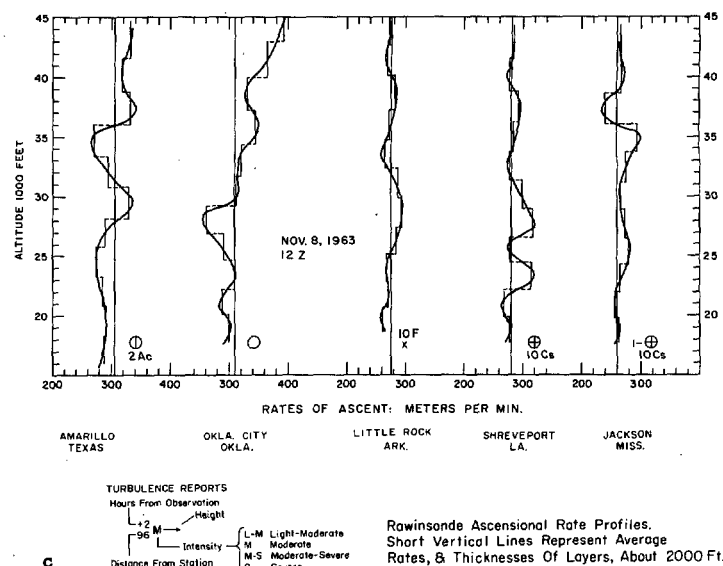
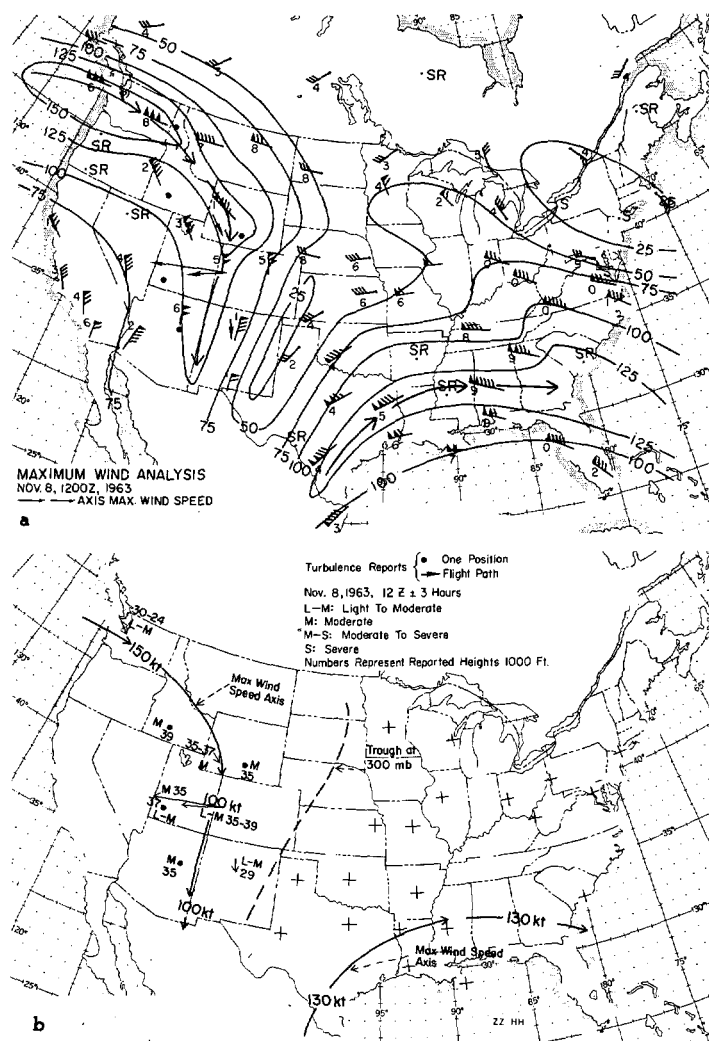


FIGURE 1.—(a) Isotach analysis at the level of the maximum wind speed (in knots) near the tropopause, for 12 GMT, November 8, 1963. Wind speeds and directions are shown with the usual symbols. (b) Geographic location, intensity, and height (in 1,000's ft.) of pilot reports of clear air turbulence (CAT) within ± 3 hr. of observation time for 1a. Same pilot reports are also plotted on 1a. The rawinsonde stations used in the ascensional rate study are marked with crosses (+). (c) Rawinsonde ascensional rate profiles for five stations for observation time of 1a. These stations were chosen because of their location with respect to the most concentrated region of turbulence as it progressed eastward. The average ascensional rate from the surface to 50,000 ft. is shown by the vertical line through the profile. Short vertical lines represent average rates and thicknesses of atmospheric layers between 5th contacts of the rawinsonde pressure switch. Ascensional rate changes, layer to layer, are shown by horizontal distances between these short vertical lines. At this observation the turbulent region was west of the stations. Ascensional rate changes are relatively small, representative of those outside the turbulent region.

2. RAWINSONDE ASCENSIONAL RATES

In reviewing data from which rawinsonde ascensional rates might be computed, it seemed important to investigate large-scale features of ascensional rates over fairly thick layers of the atmosphere, to use existing observational techniques and compilations of data wherever possible, and to use methods readily adaptable to computer techniques. Ascensional rates computed from the "altitude" and "elapsed time" tabulations of the winds-aloft computation sheets (WBAN-20) seemed to possess these desirable features and were used in this study.

These data provide ascensional rates for about 10 to 12 layers, 2,000 to 2,500 ft. thick, between about 20,000 ft. and 45,000 ft. in altitude. Ascensional rates were computed for 20 stations located within and around the turbulent region near the trough and downstream from it for all observations of the five-day study period.

3. RELATION OF IRREGULARITIES OF ASCENSIONAL RATES TO TURBULENCE

Examination of ascensional rates, computed from rawinsonde data of form WBAN-20, revealed that large irregularities frequently occurred on observations near which in place, time, and altitude clear air turbulence was reported. A large irregularity, for purposes of this discussion, may be defined as one for which the change in ascensional rates between adjacent layers is 25 percent, or greater, of the average ascensional rate for the observation computed from the surface to about 45,000 ft. Those rawinsonde observations outside the turbulent region usually showed much smaller irregularities than those within the turbulent region.

The rawinsonde irregularities should not be expected to correspond in all cases to pilot reports of turbulence because of the nature both of the reports and of turbulence. Pilots at their option report only the areas of turbulence

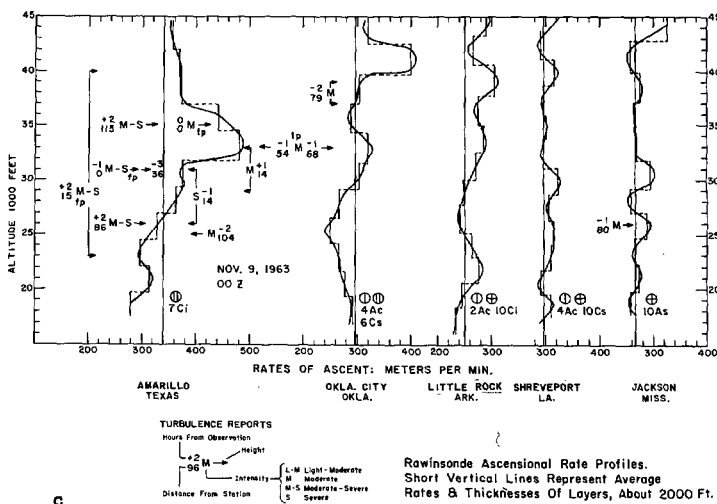
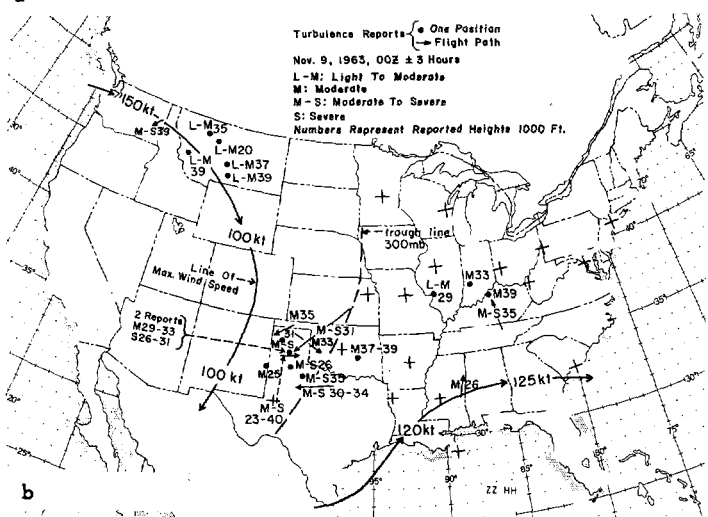
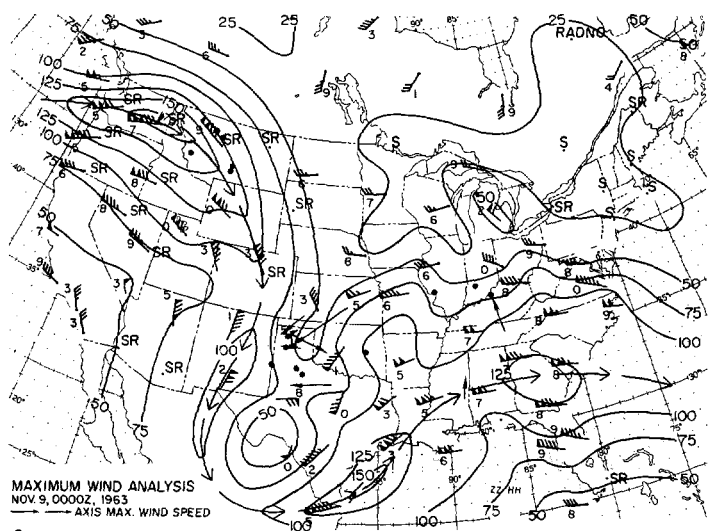


FIGURE 2.—(a) Isotach analysis (as in 1a) for 00 GMT November 9, 1963. (b) CAT reports (as in 1b) for ± 3 hr. about time of 2a. (c) Rawinsonde ascensional rate profiles for time 2a. All lines and symbols have same meaning as figure 1. The large ascensional rate anomaly, 30,000 to 35,000 ft., at Amarillo, Tex. (and the one at Oklahoma City, Okla. about 40,000 ft.) corresponds in height to nearby pilot reports of CAT. A small wave-like anomaly at Jackson, Miss. corresponds in height with a layer of high moisture content and large vertical wind speed shear. This type anomaly, though not considered in this study, may be significant for CAT. Moderate turbulence was reported nearby.

which are encountered. There may have been no turbulence or simply no reports in the unreported areas or there may have been no flights over these areas at the time, or pilots may have avoided certain altitudes for which turbulence was forecast.

Further, reported turbulence within 100 mi. of thunderstorm activity has been eliminated from the plotted maps. Thus a large irregularity without reported turbulence does not preclude the occurrence of turbulence at the place, time, and altitude of the observation. Because of the everchanging nature of turbulence it seems quite possible that an aeroplane might experience turbulence whereas the rawinsonde balloon, being at a somewhat different position in place and time, might not traverse the same turbulent element or in fact might not traverse any turbulence. For these reasons pilot reports may need to be supplemented by more direct measurements of turbulence to establish a relation with large ascensional rate changes.

Notwithstanding these difficulties, it seems important to call attention to some interesting features of this study. Though it is difficult to imagine that any particular element (or eddy) of turbulence is maintained for more than a short time, the conditions which produce turbulence may be maintained for several hours or more as the synoptic-scale pattern progresses through its life cycle. This concept allows for a turbulent region to exist for a period of time, all the while progressing in position and changing in time as the generating conditions change. The turbulent elements produced within this generating region may be imagined to exist a much shorter length of time and to occur at random in time and space within the region. The turbulent region near the trough of this study situation may be considered in terms of this description.

If then the large irregularities of rawinsonde ascensional rates are related to such a turbulent field they should also change in time and place with the reported turbulence.

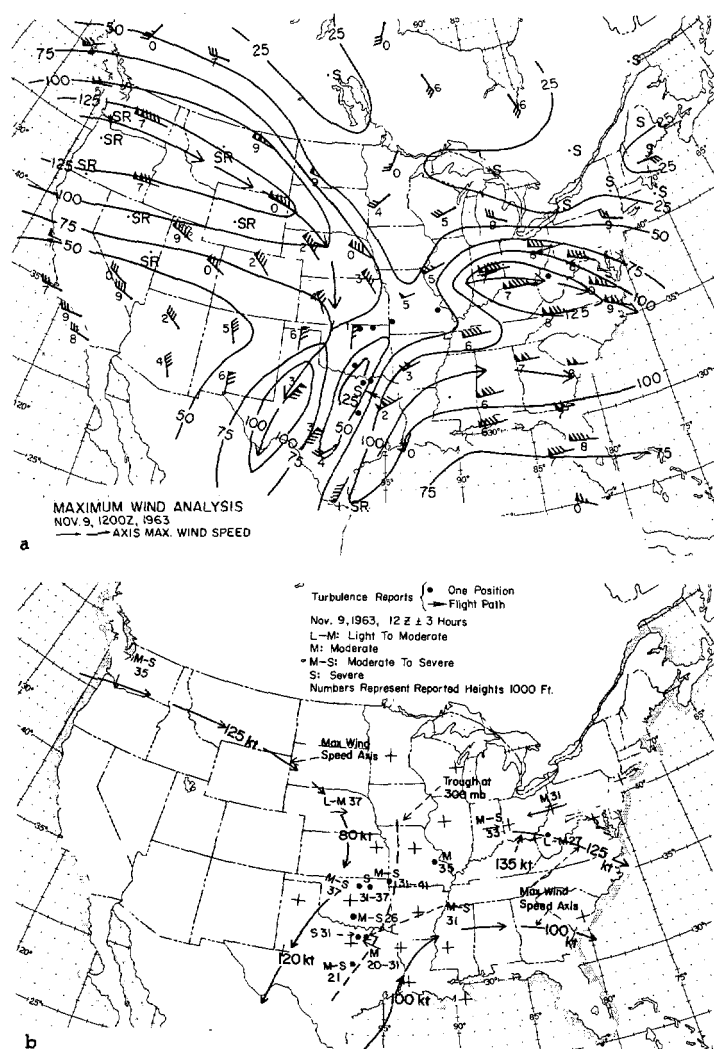


FIGURE 3.—(a) Isotach analysis (as in 1a) for 12 GMT November 9, 1963. (b) CAT reports (as in 1b) \pm 3 hr. about time of 3a. (c) Rawinsonde ascensional rate profiles for time 3a. All lines and symbols have same meaning as figure 1. The region of turbulence has progressed eastward. Ascensional rate anomalies at Oklahoma City, Okla. and Shreveport, La. correspond in height to nearby CAT reports. Data from Fort Worth, Tex., with several nearby CAT reports, were not used because of rain during the observation. A small anomaly (16 percent) occurred in the Fort Worth observation.

Though this picture may be over-simplified, it seems to describe the most outstanding feature of this study. In the region of the trough, irregularities of ascensional rates occurred successively in space and time at several stations, always progressed eastward, and usually, though not always, possessed different characteristics at different stations as illustrated in figures 1 to 5. The altitudes of the irregularities are usually near the altitudes of the turbulence reports.

The jet stream near the tropopause and its relation to the 300-mb. trough is shown in figures 1a, b to 5a, b for five successive observations. Initially the jet stream moved around a well-developed trough. As the system moved eastward the jet developed across the trough (see fig. 4a) leaving a closed Low to the south. Pilot reports of turbulence, within \pm 3 hr. of each scheduled rawinsonde observation, are plotted in figures 1b to 5b. Rawinsonde ascensional rates and nearby pilot reports, plotted as a function of altitude, are shown in figures 1c to 5c for five stations. A horizontal arrow indicates a report at one

level, a vertical line with arrows indicates a report between two levels.

Examination of this sequence of observations in detail shows that the region from Amarillo, Tex. to Jackson, Miss. was free of turbulence within \pm 3 hr. of the 12 GMT observation of November 8, 1963, as shown in figure 1. Ascensional rate curves for stations in this region were likewise relatively uniform. A high concentration of turbulence occurred near the trough in the Texas-Oklahoma region (concentrated principally around Amarillo) during the 6-hr. period centered on the next rawinsonde observation (00 GMT November 9), as shown in figure 2. The ascensional rate curve for Amarillo (fig. 2c) showed a large change (31 percent) or anomaly between about 30,000 and 38,000 ft., corresponding in height to nearby turbulence reports. An anomaly at Oklahoma City, about 40,000 to 44,000 ft., was rather high for verification, though one pilot reported moderate turbulence nearby. Another pilot reported moderate turbulence near Jackson, Miss. at a height corresponding to a

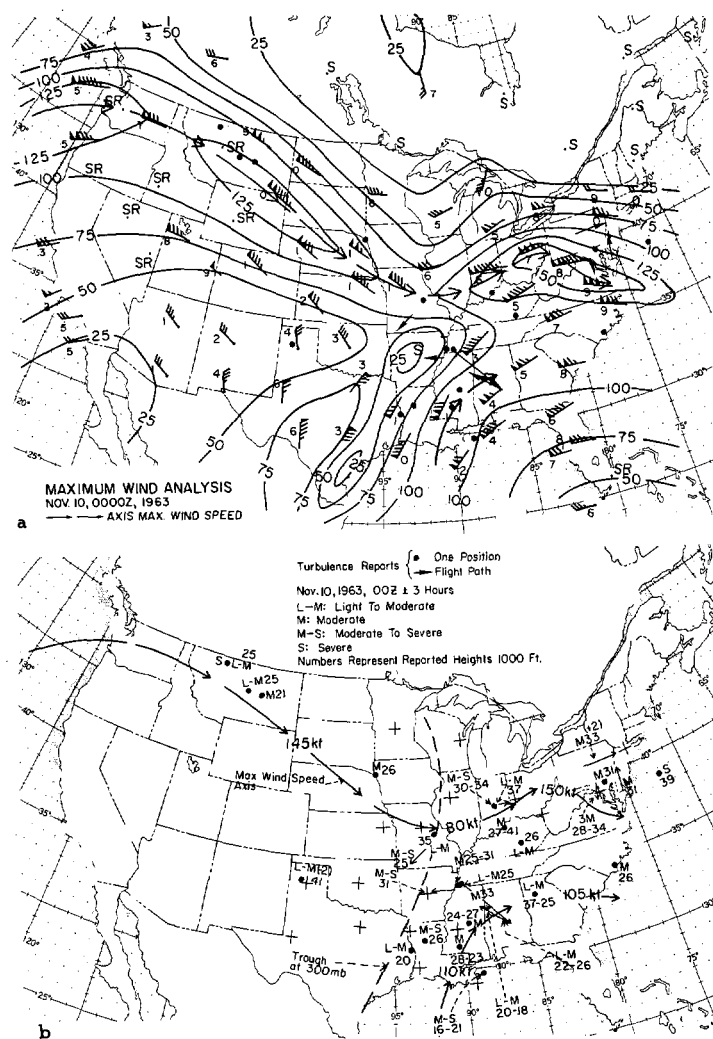


FIGURE 4.—(a) Isotach analysis (as in 1a) for 00 GMT November 10, 1963. (b) CAT reports (as in 1b) ± 3 hr. about time of 4a. (c) Rawinsonde ascensional rate profiles for time 4a. All lines and symbols have same meaning as figure 1. The region of turbulence has progressed farther eastward. The large ascensional rate anomalies at Little Rock, Ark., and Jackson, Miss. (and a smaller one, 23 percent, at Shreveport, La.) correspond in height to nearby CAT reports.

small "wave-like" anomaly (only 15 percent). Little Rock and Shreveport were both without reports of nearby turbulence and the ascensional rate profiles were relatively smooth.

At 12 GMT November 9 the trough was east of Oklahoma City. The majority of the turbulence reports were west of the front (see fig. 3). Large ascensional rate changes occurred at Oklahoma City and Shreveport again corresponding in height to the turbulence reports (fig. 3c). The profiles for Amarillo, Little Rock, and Jackson were relatively smooth and all were without reports of turbulence. At 00 GMT November 10, large ascensional rate anomalies occurred at Little Rock and Jackson at heights corresponding to nearby reports of turbulence (see fig. 4). At the next observation turbulence had primarily dissipated (fig. 5) and ascensional rate profiles were relatively smooth.

A time sequence of ascensional rate profiles is shown in figure 6 for Jackson, Miss. Again, nearby turbulence in time and place coincides well with the heights of large

ascensional rate changes. Also successive 6-hr. observations, for example, November 9, 18 GMT to November 10, 00 GMT, suggest the possibility of persistence of large irregularities over more than a 3-hr. period.

From this interesting sequence of turbulence observations it may be inferred that a turbulent region moved eastward with time in such a manner as to occur near successive rawinsonde observations, both in time and space. Large percentage variations in ascensional rates, with respect to the average for the observation, occurred on nearby rawinsonde observations and at altitudes which agree well with the turbulence reports. It seems reasonable to assume that these large variations of ascensional rates resulted from the turbulent atmosphere itself or from the generating region in which the clear air turbulence occurred.

The distribution curve of ascensional rate differences for all data (20 stations for 5 days), representing 2,100 observations, is shown in figure 7. From this curve a standard deviation of about 30 m./min. is obtained.

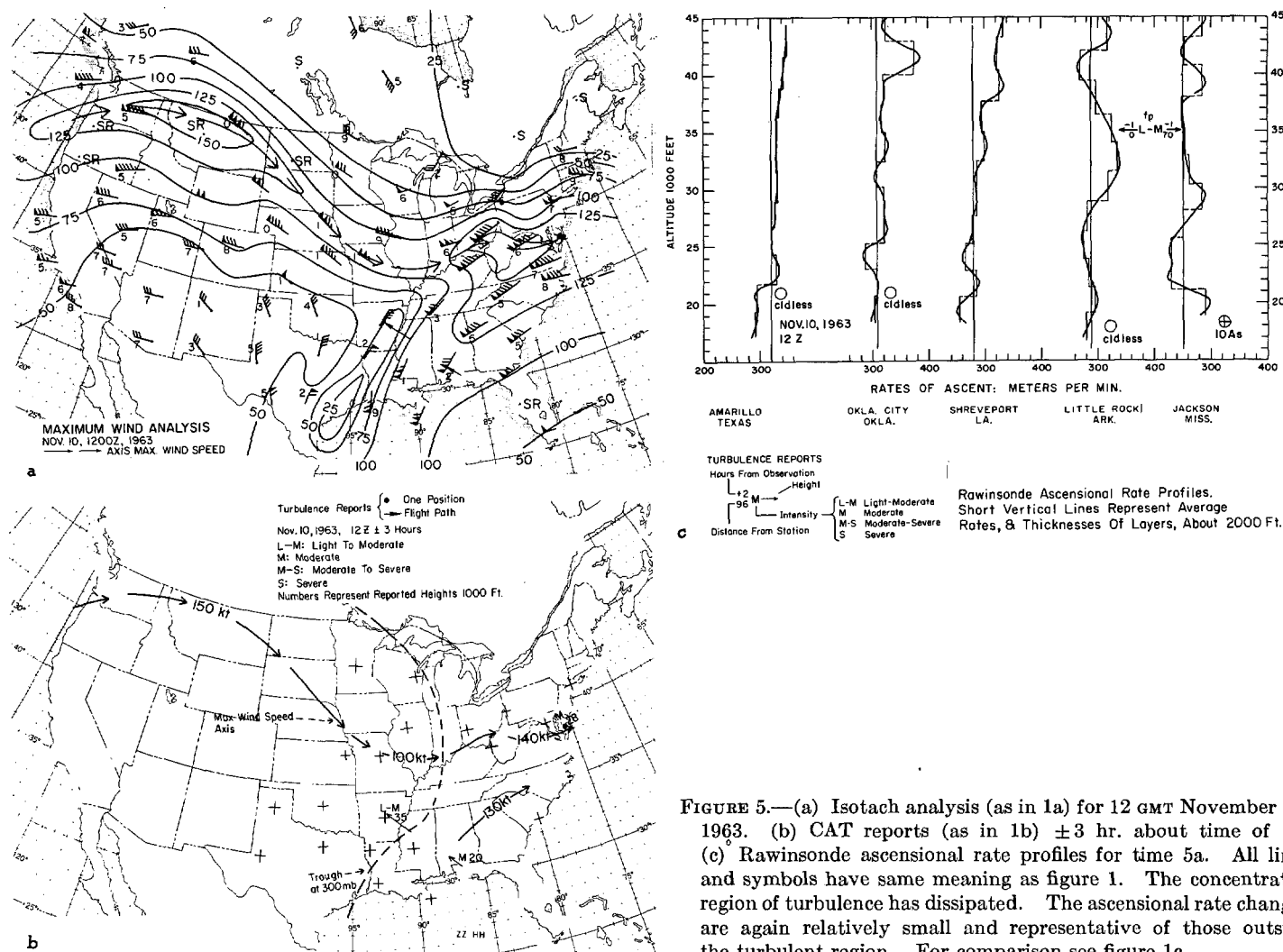


FIGURE 5.—(a) Isotach analysis (as in 1a) for 12 GMT November 10, 1963. (b) CAT reports (as in 1b) ± 3 hr. about time of 5a. (c) Rawinsonde ascensional rate profiles for time 5a. All lines and symbols have same meaning as figure 1. The concentrated region of turbulence has dissipated. The ascensional rate changes are again relatively small and representative of those outside the turbulent region. For comparison see figure 1c.

The computed standard deviation of the normalized differences, i.e., the ascensional rate differences from layer to layer divided by the average ascensional rate for the observation, is 10 percent. This is in agreement with the value of 30 m./min., since average ascensional rate for the observation is about 300 m./min. The index value of 25 percent (assigned by definition) represents 2.5 standard deviations, and on this basis deviations of 25 percent or more are considered significant for this study.

Table 1a summarizes those rawinsonde observations possessing indices (indicated as I) of 25 percent or more occurring with and without clear air turbulence (CAT) within 100 n. mi. and ± 3 hr., and those without these indices occurring with and without CAT. The number of observations which would be expected in each of these categories is shown in table 1b, assuming these are chance occurrences of unrelated events.

The result indicates a very small probability that these are chance occurrences of turbulence reports near in

time and place to large changes of rawinsonde ascensional rates.

Because of the initial success of this preliminary study, the investigation is being extended to cover a larger portion of the United States for special clear air turbulence

TABLE 1.—Number of rawinsonde observations with and without ascensional rate indices (changes from layer to layer of 25 percent or more) for the 5-day period occurring with and without clear air turbulence as observed and as expected assuming chance occurrences of unrelated events

	(a)			(b)		
	Number observations observed			Number observations expected		
	With CAT	Without CAT	Total	With CAT	Without CAT	Total
With I.....	15	21	36	5	31	36
Without I.....	12	142	154	22	132	154
Total.....	27	163	190	27	163	190

Chi square = 28.5, probability < 0.1 percent.

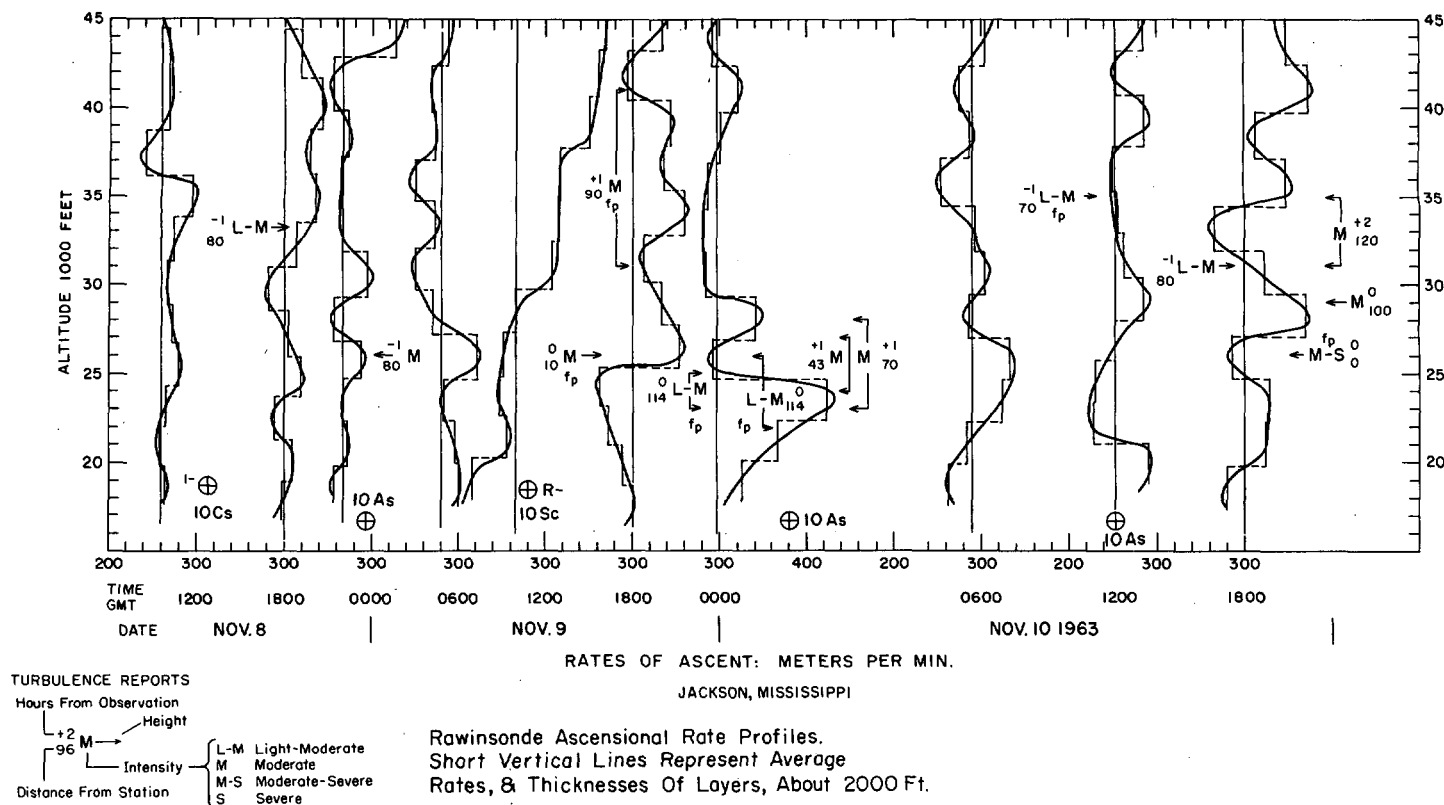


FIGURE 6.—Rawinsonde ascensional rate profiles for Jackson, Miss. for successive 6-hourly observations beginning 12 GMT November 8, 1963 and ending 18 GMT November 10, 1963, showing correspondence between large changes of ascensional rate on 18 GMT November 9, 00 GMT November 10, and 18 GMT November 10, 1963 with pilot reports of nearby CAT.

collection periods, in the hope that a relationship can be established between clear air turbulence and large ascensional rate variations of rawinsonde observations. Success in this endeavor would highlight an immediate new application of real time data from the operating network of upper-air soundings to locate and follow clear air turbulence.

4. ERRORS OF THE RAWINSONDE BALLOON SYSTEM

This weather sequence fortunately represented a clear air turbulence situation, especially in the Texas, Oklahoma, Arkansas, and Mississippi region. Thunderstorm activity, rain, and below freezing clouds of extensive thickness were not troublesome for the selected stations. Obviously ascensional rates of rawinsonde balloons ascending through precipitation may be highly variable. Ice may form on the balloon and cause further erratic motions. These factors present complicating features in this and other studies which must be resolved.

The range of Reynolds numbers experienced by the radiosonde balloon in flight is a disturbing factor. The balloon is of a soft, extensible, neoprene material. It approximates a tear drop shape at release, but assumes a nearly spherical shape some time during flight. If we assume an oblate spheroid, a standard atmosphere, and a rate of ascent of 4.5m./sec., calculations indicate the

Reynolds number of the 600-gm. balloon is about 5×10^5 near the surface and reduces to about 3×10^5 at 35,000 ft. These values are unfortunately near the critical Reynolds number and variations in balloon shape and ascensional rate may cause the drag coefficient to change. On the basis of these assumed Reynolds numbers the drag coefficient would be expected to increase with altitude with

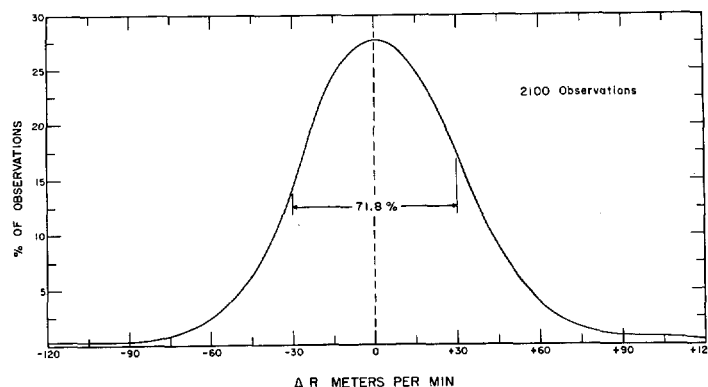


FIGURE 7.—Distribution curve for all ascensional rate changes between layers (2,100 observations) from 16,000 to 45,000 ft. for the 20 stations. The distribution is approximately normal with a standard deviation of about 30 m./min.

consequent decrease in ascensional rate. No attempt has been made to evaluate this problem. It is assumed for the time being that the motions induced in free flight of the rawinsonde balloon, by variations in the drag coefficient, would not extend through the 2,000 to 2,500-ft. thicknesses used to calculate these rates of ascent [4].

Meaningful variations in balloon ascensional rates must be in excess of errors which may be inherent in rawinsonde data. Only those errors which occur between two levels have to be considered. For a thickness of 2,000 ft. the error in thickness resulting from a 1° C. error in temperature would be about 7 ft., and for 3,000-ft. thickness the error would be about 12 ft. A corresponding error in thickness resulting from a pressure error of even 3 mb. would be appreciably smaller [5]. For practical purposes these errors are neglected. However, rather large errors may be introduced through plotting and reading the heights from the adiabatic charts. A maximum reading and plotting error is estimated to be about 300 ft., giving a root-mean-square estimate of 100 ft., or 5 percent of the total thickness. The times of the making of the 5th conducting contacts are printed automatically on the wind angle tapes to the nearest 0.05 min. On this basis the maximum error between two levels would be 0.1 min. The minimum time to traverse the 2,000-ft. thickness was 1.6 min. Thus a maximum error in time was about 7 percent or 140 ft. Again a root-mean-square estimate would be 47 ft., giving a combined root-mean-square error (estimate) of 110 ft. or about 6 percent of the total thickness of the layer. Thus, errors from the rawinsonde system would be expected to cause variations in the ascensional rate of no more than 6 percent for 68 percent of the time, and no more than 12 percent for 95 percent of the time, assuming of course a normal distribution of reading, plotting, and timing errors. This estimate is in agreement with the standard deviation of 10 percent computed from the observed values of all ascensional rate changes between levels.

5. CONCLUDING REMARKS

This discussion proposes only to bring to the attention of interested meteorological investigators the possible relation between large irregularities of rawinsonde balloon ascensional rates and nearby cases of reported clear air turbulence. The close association reported here does

not appear to be accidental. Other studies in progress should show if indeed such a relationship exists.

At this time causal relations have only been surmised. It seems reasonable that turbulence could cause large variations in rawinsonde ascensional rates by phenomena such as vertical currents, variations of drag coefficient of balloon resulting from turbulence, and by true eddy motions or turbulence produced by wind shear. Initially in the investigation it was almost immediately apparent that there was a magnitude of ascensional rate variation that could only be associated with such vertical inhomogeneities of the environment.

A careful study of the ascensional rate variations and of the errors of the measurements not only reinforced this impression, but provided an increasing degree of confidence in the definition of a large irregularity relatable to turbulence as being one for which the change in ascensional rates between adjacent layers is 25 percent or more of the average ascensional rate for the observation.

Encouraged by these results we are continuing the study to cover a larger portion of the United States for special clear air turbulence collection periods. If a relationship between clear air turbulence and large rawinsonde ascensional rate changes exists, it seems possible to use these data on a real time basis to detect and track clear air turbulence.

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